AFFORDABLE DESIGN: A METHODOLOGY TO IMPLEMENT PROCESS-BASED MANUFACTURING COST MODELS INTO THE TRADITIONAL PERFORMANCE-FOCUSED MULTIDISCIPLINARY DESIGN OPTIMIZATION

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Abstract

The primary objective of this paper is to demonstrate the use of process-based manufacturing and assembly cost models in a traditional performance-focused multidisciplinary design and optimization process. The use of automated cost-performance analysis is an enabling technology that could bring realistic process-based manufacturing and assembly cost into multidisciplinary design and optimization. In this paper, we present a new methodology for incorporating process costing into a standard multidisciplinary design optimization process. Material, manufacturing processes, and assembly processes costs then could be used as the objective function for the optimization method. A case study involving forty-six different configurations of a simple wing is presented, indicating that a design based on performance criteria alone may not necessarily be the most affordable as far as manufacturing and assembly cost is concerned.

Introduction

The Multidisciplinary Design Optimization (MDO) methodology exploits the synergism of mutually interacting phenomena. The readers are referred to recent review articles on MDO. [1,2] Traditional MDO tends to ignore cost and focuses primarily on vehicle performance criteria such as lift, drag, and range. If cost is included at all, then it is typically based solely on the weight of the vehicle. But this is inadequate and could even be misleading. High manufacturing cost could easily overwhelm any incentive to improve the design to the point of forcing the cancellation of the entire project. Determining the cost of manufacturing and assembly processes has been elusive in the past because of the difficulty of correctly modeling the cost of these processes.

Typically the MDO processes focus on either optimizing the vehicle aerodynamic performance[3] or minimizing its structural weight.[4-5] The weight is indirectly related to the manufacturing cost, and the aerodynamic performance is related to operational cost. Both weight and performance play an important role in life-cycle cost. But they are not accurate for estimating the process-based manufacturing and assembly cost (PBMAC), which is directly related to the acquisition cost. Unfortunately it has been difficult to model the PBMAC in term of typical parameters and design variables used in a traditional MDO process. The purpose of this paper is to demonstrate the use of a PBMAC modeling tool with a performance analysis tool for cost-performance optimization.

For our study, we have chosen to use the COSTRAN™ϴ code,[6] which is a commercial PBMAC. This code is an offshoot of a decade-long NASA effort[7] in developing PBMAC tools that is

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traditionally used for aircraft trade study. The COSTRAN™ model is function of individual component parts such as spars, ribs, and skin, and it is a useful tool during the conceptual design phase of an aircraft. The goal of this paper is to demonstrate the use of commercial PBMAC in a traditional performance-focused MDO. The focus of this work is to determine the "what" (interface variables) and the "how" (interface methods) of integrating PBMAC tool with high-fidelity disciplinary models such as Finite Element Methods (FEM) structural models and Computational Fluid Dynamics (CFD) aerodynamics models. In the rest of this paper, the PBMAC model is first introduced. This will be followed by illustrative results obtained for the design of a generic wing.

Process-Based Manufacturing and Assembly Cost Model (PBMAC)

The published literature abounds with articles and textbooks that advocate various PBMAC models.[8-11] A majority of these models rely on empirical data. In general, when manufacturing and/or assembly time is plotted against some design parameter on a log-log paper, a power law relationship between the variables can be determined. This procedure is the basis for a large number of Cost Estimating Relationships (CER) widely used in the industry. Another popular cost estimating procedure is the Response Surface Methodology (RSM) that relies primarily on multiple regression analysis.[12] Finally the Genetic Algorithm (GA) is another cost estimating procedure tackling the problem from the standpoint of a biological phenomenon that enhances the successful processes while progressively eliminating the unsuccessful ones.

All of the cost estimating methods mentioned above suffer from the following drawbacks: 1- Complete dependency on existing data, 2- Application is limited to the range of available data, and 3- Unnecessary complication for early design optimization. Readers are referred to the literature for explanation of the drawbacks mentioned above.[13-14]

The work presented in this paper is supported by a commercial PBMAC.[6,7] The fundamental tenet of this PBMAC is a first order cost model first proposed in 1994.[15] This model was born out of an observation that many manual as well as automated processes can be represented as dynamic systems with first-order velocity response to a step input as mathematically represented by the following equation:

$$V = V_0(1 - e^{-t/\tau}) \tag{1}$$

where V_0 is the steady-state process velocity, τ the dynamic time constant, and t the process time.

In general, t is governed by a major geometric property of the part, which could be its length, surface area, or volume. Using the terminology of reference 15, this property is designated as λ, the extensive variable for the process.

The process velocity V can be equated to the first time derivative of λ, i.e. $V=d\lambda/dt$. λ can therefore be obtained by integration of V over time, resulting in

$$\lambda = V_0[t - \tau(1 - e^{-t/\tau})] \tag{2}$$

Equation 2 cannot be inverted explicitly for t. However two approximations can be made depending on the value of t relative to τ such that:

a- For $t \ll \tau$: $t \cong \sqrt{(2\tau\lambda)/V_0}$

b- For $t \gg \tau$: $t \cong \tau + \lambda/V_0$

As suggested by Mabson (reported in reference 16), the above approximations can be combined into a single hyperbolic relation as followed:

$$t = \sqrt{(\lambda/V_0)^2 + (2\tau\lambda/V_0)} \tag{3}$$

The validity of equation 3 can be seen in figure 1 shown below. Other proofs are available in references 14 - 16.

As indicated in reference 16, a total of 18 base time equations have been identified to directly relate the process time to the extensive variable under various conditions of operation. Bao provided a few case studies to illustrate the use of these equations.[17]

To illustrate the use of equation 3, consider the fabrication of a front spar for wing construction. Experience indicates that the V_0 and τ values for a typical spar are respectively 2.4624 and 3.6934E+04. The extensive variable, λ, was determined to be the wetted area, i.e. area receiving machining, of the spar.

Therefore, if the spar's wetted area is 100 in^2, then the fabrication time will be approximately 1732 minutes. Note that this fabrication time constitutes an overall time estimate without knowing all the details of part preparation, fabrication, and quality control/inspection requirements. During conceptual design phase, this time estimate is probably all that the designer needs to know for fabrication cost.

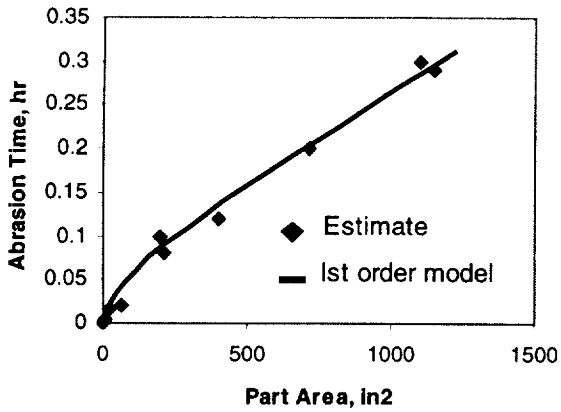

Figure 1- First-Order fit through industry estimates for abrasion operations (Reproduced from reference 15).

Preliminary Results

For the purpose of demonstration, we have selected to use a generic wing, which is made of two spars, five ribs, and skin. Figure 2 shows the CAD representation of the generic model. The results are presented for two test cases: 1) cost comparisons for forty-six different concepts, and 2) cost optimization of generic wing concept.

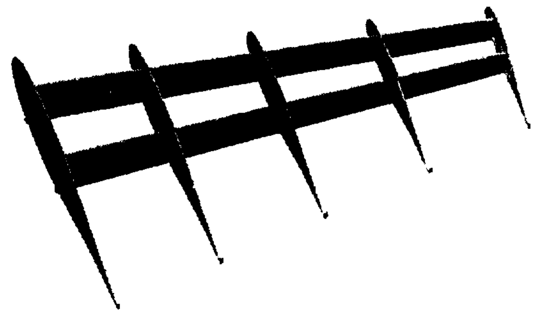

Figure 2 CAD representation of a generic wing.

This model was parameterized using Multidisciplinary Aero/Structural Shape Optimization Using Deformation (MASSOUD[18]) code. The MASSOUD code is based on a novel parameterization approach for complex shapes suitable for a multidisciplinary design optimization application. The approach consists of three basic concepts: 1) parameterizing the shape perturbations rather than the geometry itself, 2) utilizing Soft Object Animation (SOA) computer graphics algorithms, and 3) relating the deformation to aerodynamics shape design variables such as thickness, camber, twist, shear, and planform.

The MASSOUD formulation is independent of grid topology, and that makes it suitable for a variety of analysis codes such as CFD and Computational Structural Mechanics (CSM). The analytical sensitivity derivatives are available for use in a gradient-based optimization. This algorithm is suitable for low-fidelity (e.g., linear aerodynamics and equivalent laminated plate structures) and high-fidelity analysis tools (e.g., nonlinear CFD and detailed Finite Element (FE) modeling).

Figure 3 shows the parameterized model of a generic wing shown in Figure 2. This model has forty-five design variables, which consist of planform, twist, shear, camber, and thickness.

Each set of forty-five design variables constitutes a design concept. All together, forty-six different design concepts were investigated. The basis for cost estimation per design concept is indicated in tables 1 and 2.

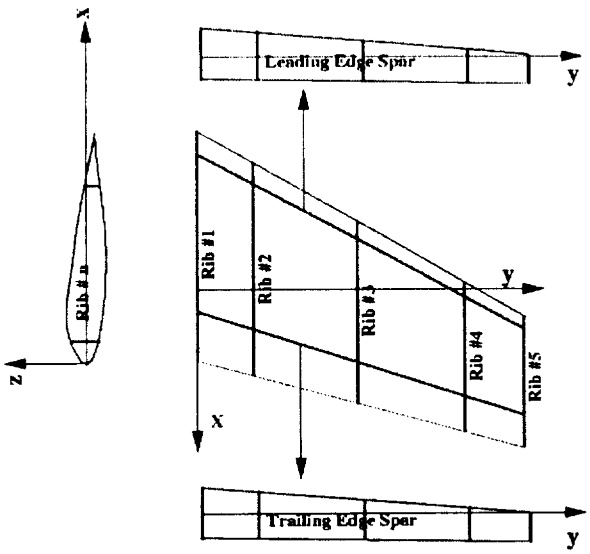

Figure 3 Parameterized model of the generic wing.

Table 1: Basis for Cost Estimation of Generic Wing, V_0 and τ

Material: Aluminum	V_0	τ	Extensive Variable[†]
Skin Fabrication	1.228	0.843	A
Rib Fabrication	0.836	1.122	A
Spar Fabrication	1	1	A
Wing Assembly	1	1	B
Material: Composite	V_0	τ	Extensive Variable
Skin Fabrication	0.871	1.188	A
Rib Fabrication	0.334	0.280	A
Spar Fabrication	0.588	1.700	A
Wing Assembly	0.714	1.399	B

[†] Where, A is wetted area in inch^2 and
B is perimeter in inch.

Table 2: Basis for Cost Estimation of Generic Wing, Common Parameters

Labor	$60/Hour
Material Cost:	
- Skin	$20/Lb
- Rib	$12/Lb
- Spar	$15/Lb
- Fasteners	$.20/Unit
Set Up and Delay Time per operation	Not considered; Recurrence cost only

The interpretation of tables 1 and 2 should be as follows: the published values of V_0 and τ for an average spar were used as base values. The V_0 and τ for all other wing components such as rib and skin were expressed in relative term compared to those of the base spar. Similarly the V_0 and τ for the assembly of a typical wing were also used as base values. Values for the composite wing assembly were expressed in relative term compared to those of the aluminum wing assembly. It should be noted that wing assembly process should be separated from fabrication of skin, spar and rib because the former process depends critically on the perimeter while the latter process depends on the wetted area. Expressing all V_0 and τ relative to those of the spar would be erroneous. Data in table 2 are representative of each of the indicated elements in a given year.

For each design concept, the wetted areas for upper and lower skin, front and rear spar, and average rib were determined. Next, the perimeter for each of the above components was determined. Finally the data indicated in tables 1 and 2 were used to, first determine the fabrication cost of each component, second their assembly cost, and third and finally the total cost per design concept. Figure 4 shows the cost comparison for all forty-six different concepts, based on discrete choices of materials and shapes for a given structural topology, and given manufacturing and assembly processes.
Figure 5 shows the cost comparison of individual cost factors for a given concept.

For the first test case, i.e. aluminum wing, the parameterized model was embedded into an optimization process as shown in figure 6.

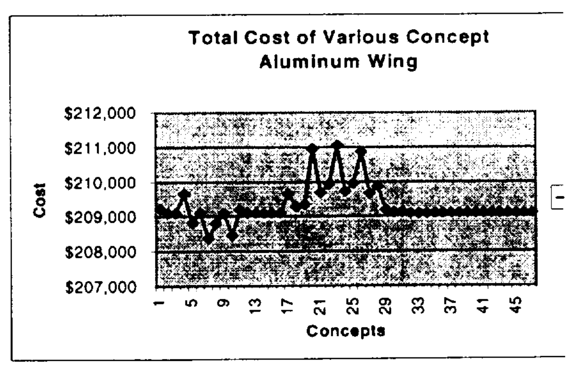

Figure 4 Cost comparisons for forty-six different concepts.

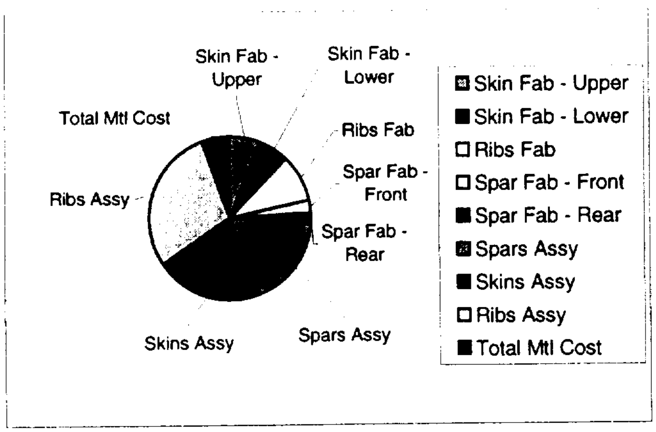

Figure 5. Cost comparisons of individual cost factors for a generic wing.

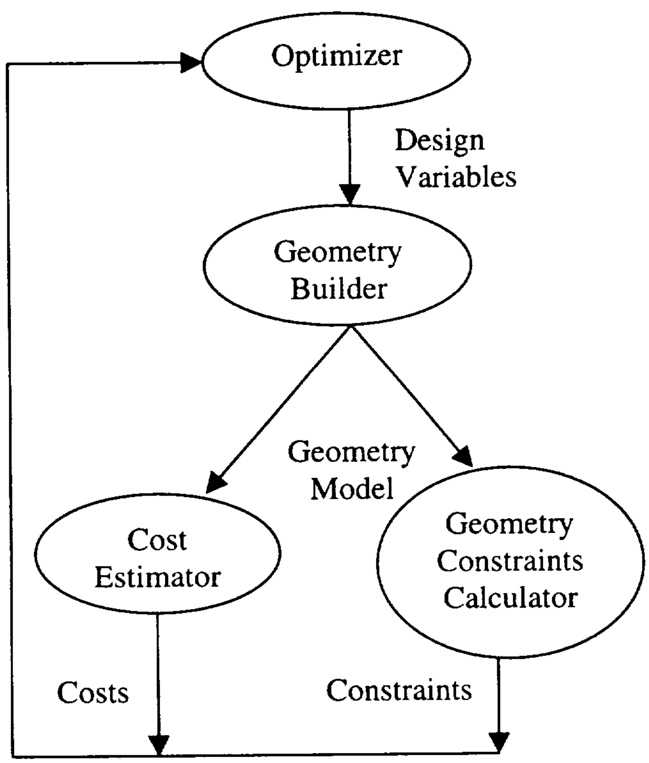

Figure 6. Optimization Process

The optimization process is made of four modules: optimizer, geometry builder, cost estimator, and geometry constraints calculator. The optimization code CONMIN[19] was used for the optimizer module. As mentioned before, the MASSOUD code was used to parameterize the geometry. The cost estimating concept described previously was used to estimate the cost of a generic wing. The total wetted skin, rib, and spar areas were constrained to stay below the baseline design.

Figure 7 shows preliminary optimization result for the generic wing shown in figure 2. The cost was reduced by more than 1.8%.

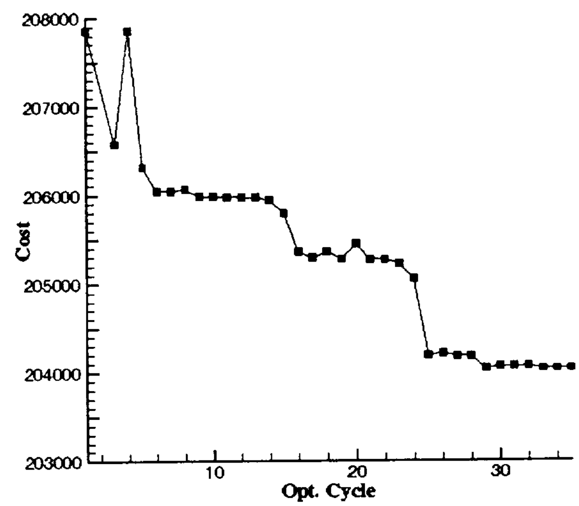

Figure 7. Cost optimization.

Discussion

Cost consideration is among the most important elements in any multi-disciplinary design optimization scheme. There are many kinds of cost involved in a typical airplane program. As described by Roskam,[20] there are costs associated with the planning and conceptual design, with preliminary design and system integration, with detail design and development, with manufacturing and acquisition, design and system integration, with detail design and development, with manufacturing and acquisition, with operation and support, and with disposal. This paper deals strictly with the first type of costs, notably costs associated with the planning and conceptual design. As indicated earlier, the MDO community so far tends to treat cost as solely based on the weight of the vehicle. The case studies included in this paper indicate that fabrication and assembly costs are much more significant than material costs – as expressed by weight- and should be part of the optimization scheme.

Even at the conceptual design phase, there is a need to incorporate the costs of fabrication and assembly of the major components such as spars, ribs, and skins. Using the first design configuration as a typical design, the following table reveals how dominating fabrication and assembly costs were over material costs.

	Mtl	Mfg	Assy	Total Wing
Front Spar	5.5%	21.3%	73.2%	12.3%
Rear Spar	4.3%	19.5%	76.2%	11.4%
5 Ribs	3.9%	23.4%	72.7%	39.9%
Upper Skin	7.5%	33.4%	59.1%	18.4%
Lower Skin	7.6%	33.9%	58.5%	18.0%
Total Wing	5.5%	26.4%	68.1%	100%

From the above percentage table, it can be said that, in general material cost was only about 5% of the cost of fabrication and assembly. Also, fabrication cost of either spar or rib was about 30% of corresponding assembly cost, while fabrication cost of skin was about 50% of assembly cost. The numbers quoted above are close to industry standards.

As to the cost comparison of the forty-six different design concepts, while the magnitude of the overall cost reduction was less than 2%, the point was that the proposed cost model was detailed enough to accommodate all design concepts. Furthermore it could be easily incorporated in any multi-disciplinary optimization methodology.

Conclusions

We have demonstrated the use of process-based manufacturing and assembly cost models in a traditional performance-focused multidisciplinary design and optimization process. Three major conclusions can be drawn from this paper. First the weight may not be directly related to cost, and minimizing the weight without considering the manufacturing and assembly costs may increase the overall cost. Second the analytical cost models can be incorporated in a traditional MDO process. And third, the fabrication and assembly costs could drive the optimization process to minimize the actual cost of the part being considered.

References

[1] Sobieszczanski-Sobieski, J. Haftka, R.T., "Multidisciplinary Aerospace Design Optimization: Survey of Recent Developments," *Structural Optimization*, Vol. 14, No. 1, 1997, pp. 1–23.

[2] Giesing, J., and Barthelemy, J.-F. M., "Summary of Industry MDO Applications and Needs," AIAA Paper 98-4737, 7th AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, St. Louis, MO, Sep. 1 – 4, 1998. (Available electronically at http://techreports.larc.nasa.gov/ltrs/ltrs.html)

[3] Zang, T. A. and Green, L. L., "Multidisciplinary Design Optimization Techniques: implications and Opportunities for Fluid Dynamics Research," AIAA Paper 99-3798, 30th AIAA Fluid Dynamics Conference, Norfolk, VA, June 28-July 1, 1999. (available electronically at http://techreports.larc.nasa.gov/ltrs/ltrs.html)

[4] Walsh, J. L., Townsend, J. C., Salas, A. O., Samareh, J. A., Mukhopadhyay, V. and Barthelemy, J.-F.,
"Multidisciplinary High-Fidelity Analysis and Optimization of Aerospace Vehicles, Part 1: Formulation,"

AIAA Paper 2000-0418, 38th AIAA Aerospace Sciences Meeting & Exhibit, Reno, NV, Jan. 10-13, 2000.
(Available electronically at http://techreports.larc.nasa.gov/ltrs/ltrs.html)

[5] Walsh, J. L., Weston, R. P., Samareh, J. A., Mason, B. H., Green, L. L and Biedron, R. T., "Multidisciplinary High-Fidelity Analysis and Optimization of Aerospace Vehicles, Part 2: Preliminary Results," AIAA Paper 2000-0419, 38th AIAA Aerospace Sciences Meeting & Exhibit, Reno, NV, Jan. 10 – 13, 2000. (Available electronically at http://techreports.larc.nasa.gov/ltrs/ltrs.html)

[6] Proctor, M. R. and Metschan, S. L., "Data Integration and the effect on IPT cost communication," The International Society of Parametric Analysis (ISPA) & The Society of Cost Estimating and Analysis (SCEA) 1998 Joint International Conference and Educational Workshop June 1998.

[7] Ilcesicz, L. B., Mabson, G. E., Metschan, S. L., Swanson, G. D., Proctor, M. R., Tervo, D. K., Fredrikson, H. G., Gutowski, T. G., Neoh, E. T. and Polgar, K. C., "Cost Optimization Software for Transport Aircraft Design Evaluation (COSTADE): Design Cost Methods," NASA Contractor Report 4737, August 1996.

[8] Department of Defense, "Parametric Cost Estimating Handbook", Fall 1995.

[9] Northrop Corporation, "Advanced Composite Cost Estimating Manual (ACCEM)", AFFDL-TR-76-87, August 1976.

[10] Lee, P., " A Process Oriented Parametric Cost Model", AIAA/AHS/ASEE Aerospace Design Conference, Irvine, CA, February 1993, pp.1-6.

[11] Solverson, R.S., "Design to Cost with Price-H", AIAA/AHS/ASEE Aerospace Design Conference, Irvine, CA, February 1993, pp. 1-14.

[12] Unal, R., Stanley, D.O., and Joyner, C.R., "Parametric Model Building and Design Optimization using Response Surface Methods", Journal of Parametrics, Volume XIV, Number 1, 1994, pp. 81-95.

[13] Freeman, W.T., et al., "Designers' Unified Cost Model", Second NASA Advanced Composites Technology Conference, NASA Conference Publication 3154,1992, pp. 27-45.

[14] Neoh, E.T., Gutowski, T., and Dillon, G., "Framework for estimating fabrication time of advanced composites manufacturing processes", Proceedings 40th International SAMPE Symposium and Exhibition, Anaheim, CA, May 11, 1995.

[15] Gutowski, T., et al., "Development of a theoretical cost model for advanced composite fabrication", Composite Manufacturing, Volume 5, Number 4, 1994, pp. 231-239.

[16] Proctor, M.R., Metschan, S.L., and Klein, H.S., "Cost Optimization Software for Transport Aircraft Design Evaluation (COSTADE): Process Cost Analysis Database (PCAD) ", NASA Contractor Report 4739, August 1996.

[17] Bao, H.P., "Cost Estimation of Composites Manufacturing Processes Through Process Cost Analysis Database (PCAD), 1997 ASEE/NASA Faculty Summer Fellowship Report, Mechanics of Materials Branch, NASA Langley Research Center, August 1997.

[18] Samareh, J.A., "A Novel Shape Parameterization Approach", NASA/TM-1999-209116, May 1999.

[19] Vanderplaats, G.N., "CONMIN-A Fortran Program for Constrainted Function Minimization, User's Manual," NASA TM-X-62282, Aug. 1973.

[20] Roskam,J., "Airplane Design, Part VIII: Airplane Cost Estimation: Design, Development, Manufacturing and Operating", Darcorporation, 1990 Edition.